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COMPARISON OF RESPIRABLE DUST SAMPLERS IN AN UNDERGROUND HARD ROCK MINE

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ELLIOT LAKE LABORATORY

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COMPARISON OF RESPIRABLE DUST SAMPLERS IN AN UNDERGROUND HARD ROCK MINE

by

M.G. Grenier* and K.C. Butler**

ABSTRACT

Three types of gravimetric dust samplers were tested and evaluated in an underground mine. CAMPEDS personal dust samplers, York 10-mm Nylon Cyclones, and Casella MRE-113A horizontal elutriators were inter-compared along with Gillian and Dupont sampling pumps which were used on all three types of samplers. Tests were conducted at a mine with a high quartz ore content. Samplers were evaluated from the viewpoint of total and quartz respirable dust mass assessment, as well as overall performance and ease of handling.

Cyclones were found to underestimate total and quartz respirable dust when compared with the horizontal elutriator. Ratios of total and quartz dust from the elutriator to that of cyclones were 1.60 and 1.64, respectively. Ratios for elutriator to CAMPEDS dust mass were 0.92 and 0.84 for total and quartz, respectively. Both cyclones and CAMPEDS showed good reproducibility when used side by side. The design and material of the filter holder used with the cyclone samplers could lead to leakage or dust mass underestimation. The CAMPEDS' filter support grid caused a definite and unpredictable dust collection pattern on filter discs. This could affect results of X-ray diffraction analysis. Two types of sampling pumps were used with all gravimetric samplers and, except for minor details, both pumps performed satisfactorily.

A personal continuous dust monitor (GCA PDM-3 Miniram) was also evaluated during these tests. The instrument performed well and an attempt was made to correlate the concentration as given by the Miniram to the time-weighted average dust concentration measured by gravimetric samplers.

Key words: Dust samplers; Gravimetric sampling; Mining environment.

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COMPARAISON ENTRE DIVERS ÉCHANTILLONNEURS DE POUSSIÈRES INHALABLES, DANS UNE MINE SOUTERRAINE EN ROCHE DURE

par

M.G. Grenier* et K.C. Butler**

RÉSUMÉ

On a testé et évalué trois types d'échantillonneurs gravimétriques de poussières, dans une mine souterraine. On a comparé la performance d'échantillonneurs portatifs de poussières CAMPEDS, de cyclones York en nylon de 10 mm de diamètre, et d'élutriateurs horizontaux Casella MRE-113A, en même temps que la performance de pompes d'échantillonnage Gillian et Dupont que l'on a utilisées avec chacun des trois types d'échantillonneurs. On a réalisé des essais dans une mine contenant un minerai fortement quartzeux. On a évalué les échantillonneurs d'après les mesures de la masse totale et de la masse des poussières de quartz inhalables, et d'après la performance globale et la maniabilité de ces appareils.

On a constaté que, comparativement à l'élutriateur horizontal, les cyclones donnaient des valeurs inférieures aux valeurs réelles, à la fois pour les concentrations totales de poussières et celles des poussières de quartz inhalables. Les rapports des concentrations totales de poussières et des concentrations de poussières de quartz inhalables, indiquées par l'élutriateur, aux concentrations respectives indiquées par les cyclones, étaient de 1,60 et 1,64. Les rapports des valeurs de la masse de poussière indiquées par l'élutriateur dans l'un et l'autre cas, aux valeurs indiquées par l'échantillonneur CAMPEDS étaient respectivement de 0,92 et 0,84. Les cyclones et échantillonneurs CAMPEDS ont tous deux montré une bonne reproductibilité des résultats lorsqu'ils étaient utilisés conjointement. La conception et les produits entrant dans la fabrication du porte-filtre utilisé dans les échantillonneurs à cyclone pourraient entraîner une sous-estimation de la masse de

poussières, ou causer des fuites de poussières. La grille de soutien du filtre de l'échantillonneur a produit sur les disques des filtres une configuration nette mais imprévisible des dépôts de poussières. Ceci pourrait avoir un effet défavorable sur l'analyse par diffraction des rayons X. On a employé deux types de pompes d'échantillonnage avec tous les échantillonneurs gravimétriques et, à quelques détails près, les deux pompes ont fonctionné de façon satisfaisante.

On a aussi évalué au cours de ces essais un capteur de poussières, de type portatif (GCA PDM-3 Miniram). Cet instrument a donné de bons résultats et l'on a cherché à établir une corrélation entre la concentration mesurée par le Miniram et la concentration moyenne de poussières, pondérée en fonction du temps, telle que mesurée par des échantillonneurs gravimétriques.

Mots-clés : Échantillonneurs de poussières; échantillonnage gravimétrique; environnement des mines

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INTRODUCTION

The complexity of the human respiratory tract and the physics of dust and aerosol deposition have been the subject of numerous studies. Although the deposition of dust, the clearance mechanisms, and the effects of various types of dust on lung tissues are not completely understood, Lippmann has produced a review which comprehensively summarizes the problems associated with respirable dust sampling (1).

As dust-laden air is inspired, dust may deposit by impaction, sedimentation or diffusion along the respiratory tract. Dust collected at the nose, mouth and throat level is rapidly eliminated by swallowing. Dust deposited in the trachea and bronchi is swept back up by ciliated cells that line the wall of the tracheo-bronchial tree. Dust deposited in this region can be eliminated in a few hours. Beyond the bronchi lies the alveolar region. This part of the lung is penetrated by finer dust. Larger dust particles have been collected by sedimentation or by impaction at bronchial bifurcations. The alveolar region is not equipped with ciliated cells, and dust clearance has a half-life of a month or so. Furthermore, the clearance mechanisms acting at the alveolar level are not straightforward or well understood.

What is clear, however, is that parts of the respiratory tract have more or less well defined cut-sizes. When polydisperse dust enters certain regions of the tract, some dust will be deposited while finer dust will be allowed to penetrate further. Another important point is that the alveolar region, with a slow dust clearance time, is the area where insoluble dust may inflict the most serious damage.

Some knowledge of the size distribution of dust penetrating the alveoli and the relative lack of ability for clearance in this region have led some

organizations to adopt definitions of 'respirable dust'. Respirable dust in most cases is defined as that penetrating the alveoli or non-ciliated portion of the lung. The British Medical Research Council (BMRC) defines respirable dust by the penetration curve shown in Figure 1. In this model, 50% of 5.0 μm dust particles penetrate the alveolar region. This curve was chosen because it was possible to reproduce this penetration pattern by using a properly designed horizontal elutriator such as the Casella MRE-113A, a BMRC compatible sampler. The CAMPEDS two-stage impaction sampler also used here, is a personal sampler that was calibrated gravimetrically with BMRC approved elutriators.

The American Conference of Governmental Industrial Hygienists (ACGIH) has adopted a penetration curve (Figure 1) whose characteristics are closely matched by cyclone type samplers. The York 10-mm Nylon Cyclone used here is meant to have a 50% cut-size at 3.5 μm, when operated at 1.7 L/min.

It is not within the scope of this work to comment on the relative merits or disadvantages associated with either definition of respirable dust, but to analyze the performance of some dust samplers as tested in an underground environment.

INSTRUMENTS

This section describes briefly the instruments used in the course of the study.

MRE-113A HORIZONTAL ELUTRIATOR

The MRE-113A is a two-stage sampler. The first stage consists of parallel plates where non-respirable dust is settled gravitationally. The finer, respirable fraction passing through the first stage is collected on a filter disc in the second stage. The MRE-113A samplers used in this study were a modified version of the original instrument. In order to allow for

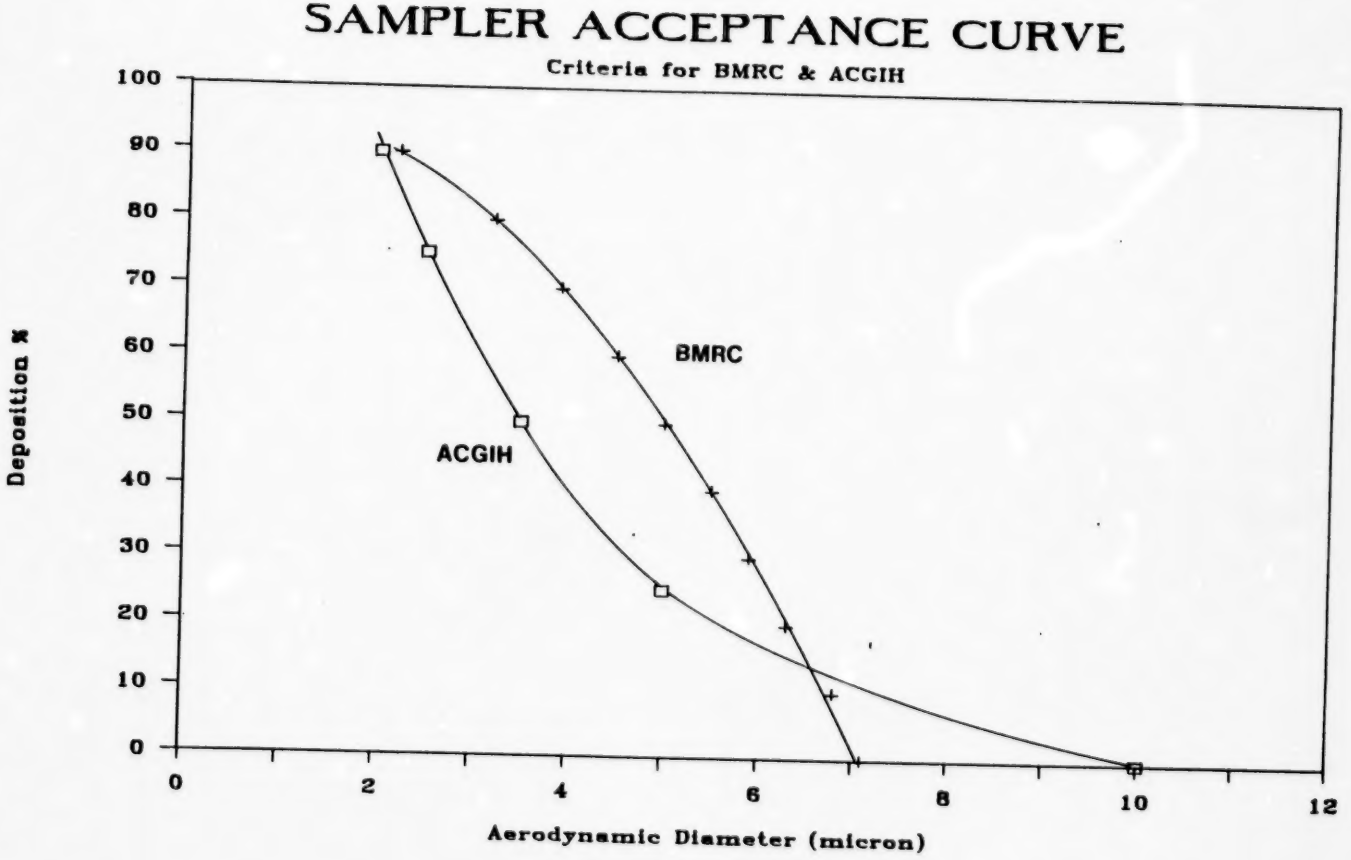

Fig. 1 - BMRC and ACGIH respirable dust curves.

quartz content determination by X-ray diffraction to be performed on filter discs, a special filter holder was designed to accommodate 25 mm diameter substrates. Furthermore, one of the four elutriating channels was blocked, which meant that the instruments would be operated at a flowrate of 1.9 L/min or 75% of the original flowrate of 2.5 L/min. The MRE-113A penetration characteristics are compatible with BMRC specifications.

CAMPEDS PERSONAL DUST SAMPLERS

The CAMPEDS samplers operate on inertial principles and are described at length elsewhere (2). They were designed to sample respirable dust according to BMRC specifications. In the first stage of the sampler, non-respirable dust is removed by two impaction surfaces. Respirable dust is collected in the second stage on a 25 mm diameter silver membrane filter disc. As is the case for the MRE-113A, filter substrates are analyzed for quartz respirable dust using X-ray diffraction analysis. The CAMPEDS are operated at a flow rate of 2 L/min.

YORK 10-MM NYLON CYCLONES

Nylon cyclones are two stage gravimetric samplers. In the first stage non-respirable particles are separated by centrifugal force and deposited in a dust trap at the bottom of the cyclone. Respirable dust remains in the air stream and leaves the cyclone to be collected in a plastic filter holder containing a 25 mm silver membrane filter disc. As mentioned before, these cyclone samplers have a penetration curve matching ACGIH specifications and were operated at the recommended flow rate of 1.7 L/min.

GCA MINIRAM PDM-3 CONTINUOUS DUST MONITOR

The Miniram is an airborne particulate monitor operating on the principle of electromagnetic radiation scattering from dust particles. The instrument continuously monitors total scattering from particles in the sensing volume. Ambient air currents and convection cause the airborne dust

to pass through the sensing chamber. The instrument sensors are adjusted to respond preferentially to particles in the 0.1 to 10.0 μm range. In this study an attempt was made to define a factor in order to convert any instantaneous reading to respirable airborne dust mass according to BMRC specifications.

SIERRA CASCADE IMPACTOR

The size distribution of ambient dust was measured with an eight-stage, radial-slot design, Sierra (now Anderson) cascade impactor. The impactor was used with a calibrated sampling pump operating at 13 L/min. Cut-sizes for the eight stages ranged between 0.2 and 13.2 μm for stages eight to one, respectively. Dust is collected on a slotted pre-weighed glass fiber substrate placed behind each stage. These substrates collect the portion of dust impacting on it according to the size cut-off of the preceding stage.

SAMPLING PUMPS

Pumps are an important part of the gravimetric sampling train. In this study, gravimetric samplers were used with pumps from two different manufacturers. These were the Dupont Model P-2500 Constant Flow Sampler and the Gilian Model HFS-113 "Hi-Flow" sampler.

The Dupont is a diaphragm pump that uses a feedback control to adjust pump speed, i.e., revolutions per minute (rpm) to maintain constant flow. The pump is quoted as being able to maintain a constant airflow rate (±5%) over a pressure drop of 3.7 kPa. The pump operates at flow rates ranging between 1.0 and 2.5 L/min. The Dupont's flow is smoothed by an accumulator.

The Gilian sampler is a piston pump. As with the previous pump, these models have a flow compensation unit and dampers to smooth out pulsations. In the high flow mode, the Gilian pump operates between 0.5 and 3.5 L/min. The instrument is equipped with a rotameter flow indicator (Dupont does not provide a visual flow indicator other than a flow Light Emitting Diode).

SITE DESCRIPTION

Tests were conducted in a belt conveyor drift of an underground hard rock mine. The airflow volume was approximately 7 m/s in a drift cross-section of about 15 m^2. The major portion of airborne contaminants was produced by a crushing operation and by the transfer point onto the conveyor approximately 37 m away from where the samplers were being tested.

All gravimetric samplers were attached securely to their respective sampling pumps. Every type of sampler was used with both Gilian and Dupont pumps. All sampling trains were hung approximately 45 cm from the back with the help of wire coat hangers. Care was taken to ensure that elutriators were set as level as possible. Samplers were centrally located with respect to the drift in rows of two or three samplers abreast. Four nylon cyclones, four CAMPEDS and two elutriators were used. All samplers were hung in an area of approximately 4.5 m^2.

The Sierra cascade impactor was also hung from the back in the centre of the drift on the return ventilation side with respect to the rest of the samplers. The Miniram continuous dust sampler was placed at eye-level to one side of the drift. Care was taken not to place the Miniram too close to the wall, thereby ensuring a representative sample.

EXPERIMENTAL CONSIDERATIONS

GRAVIMETRIC SAMPLERS AND CASCADE IMPACTOR

Filters used in all gravimetric samplers were 25 mm silver membrane discs. These had been pre-weighed after 24 hours of resting at 50% relative humidity and 18^{o}C in a dedicated weighing room. After the study, all filter discs were conditioned under similar conditions before being weighed to yield total respirable dust mass. Filters were then processed by X-ray diffraction

analysis to determine the quartz content of the sample.

Glass fiber collection substrates from the cascade impactor were weighed using a similar technique as described above, with the exception that X-ray diffraction analysis was not performed.

All sampling pumps were calibrated on a daily basis in the field. Calibration underground eliminates flow rate discrepancies due to air density changes with depth. Calibration was performed using a Gilian Buck Calibrator. Both Gilian and Dupont pumps were calibrated and adjusted at the beginning of the shift. Flowmeters on Gilian pumps were checked at regular intervals during the shift to ensure that the units were functioning properly. Dupont pumps were again calibrated at the end of the shift.

MINIRAM CONTINUOUS DUST MONITOR

The Miniram dust monitor produces a reading of dust concentration in mg/m^3, every ten seconds. Readings are printed on a digital printer in the field. During the course of sampling in the field, sensing chamber contamination occurs which results in a zero drift. To correct for this, the sensing chamber was cleaned on a daily basis and instrument zero readings were obtained at the beginning and at the end of each shift. Data values could then be corrected individually, assuming a linear zero drift effect during the sampling period.

TEMPERATURE AND RELATIVE HUMIDITY

Tests were carried out over a three day period (DAY 1 to DAY 3) at relative humidities in excess of 90% and temperatures of approximately $14^{\circ}C$. Sampling lasted on average 320 minutes per day.

EXPERIMENTAL RESULTS

GRAVIMETERIC SAMPLERS

Tables 1 and 2 list the total and quartz airborne respirable dust

concentration for all gravimetric samplers over the three day period. From these results, it appears that cyclone data are consistently much lower than both CAMPEDS and elutriator concentrations. This tendency is seen in both total and quartz respirable dust data.

Tables 3 and 4 list ratios of respirable dust concentration from the average of elutriator data on a given day divided by individual CAMPEDS and cyclone concentration for total and quartz respirable dust, respectively. The averages of these ratios are shown in Table 5. In Table 5 the uncertainty associated with each ratio is a standard deviation calculated over twelve values. For total dust, it seems that CAMPEDS samplers are in close agreement with elutriators (ratio of 0.92). For quartz respirable dust, this ratio is 0.84. This value is fairly low, but the measure of spread (standard deviation) on both ratios does not give one statistical grounds to consider them different. Nylon cyclone ratios in Table 5 are fairly high but they are nearly identical and the lower standard deviations seem to indicate a lower degree of variability compared to CAMPEDS.

Table 6 shows the percentage of quartz respirable dust measured for each type of instrument on a daily basis. From these data, it seems that even though the nylon cyclones and the elutriators do not follow similar respirable dust criteria, they measure a similar quartz percentage on all three days. The CAMPEDS quartz percentages, however, are statistically different from elutriator percentages on at least two out of three days.

MINIRAM CONTINUOUS DUST MONITOR

Figure 2 shows a continuous dust concentration profile for DAY 2. These data are obtained from the Miniram after calculating five minute averages and correcting for zero drift. The time axis is shown in minutes from 08:00 hours.

Previous experience from sampling in the area has shown that the large

Table 1 - Total respirable dust concentration (mg/m^3)

Sampler	Day 1	Day 2	Day 3
CY1	0.45	0.56	0.48
CY2	0.43	0.60	0.52
CY3	0.47	0.60	0.54
CY4	0.45	0.56	0.52
CA1	0.86	0.86	0.94
CA2	0.89	1.07	1.00
CA3	0.75	0.89	0.91
CA4	0.75	0.95	0.88
EL1	0.71	0.87	0.92
EL2	0.68	0.89	0.83

Note: CY = cyclone; CA = CAMPEDS; EL = elutriator

Table 2 - Quartz respirable dust concentration and percentage (mg/m^3), (%).

Sampler	Day 1	Day 2	Day 3
CY1	0.17 (38)	0.31 (55)	0.27 (56)
CY2	0.17 (40)	0.28 (47)	0.24 (46)
CY3	0.17 (36)	0.27 (45)	0.26 (48)
CY4	0.19 (42)	0.27 (48)	0.27 (52)
CA1	0.39 (45)	0.49 (57)	0.54 (57)
CA2	0.41 (46)	0.62 (58)	0.58 (58)
CA3	0.33 (44)	0.49 (55)	0.47 (52)
CA4	0.35 (47)	0.52 (55)	0.43 (49)
EL1	0.31 (44)	0.45 (52)	0.50 (54)
EL2	0.27 (40	0.38 (43)	0.42 (51)

Table 3 - Ratio, total respirable dust concentration from elutriator divided by concentration from cyclones or CAMPEDS.

Sampler	Day 1	Day 2	Day 3
CY1	1.56	1.57	1.83
CY2	1.63	1.47	1.69
CY3	1.49	1.47	1.63
CY4	1.56	1.57	1.69
CA1	0.81	1.02	0.94
CA2	0.79	0.82	0.88
CA3	0.93	0.99	0.97
CA4	0.93	0.93	1.00

Table 4 - Ratio, quartz respirable dust concentration from elutriator divided by concentration from cyclones or CAMPEDS.

Sampler	Day 1	Day 2	Day 3
CY1	0.71	1.36	1.70
CY2	1.71	1.50	1.92
CY3	1.71	1.56	1.70
CY4	1.53	1.56	1.70
CA1	0.74	0.86	0.85
CA2	0.71	0.68	0.79
CA3	0.88	0.81	0.98
CA4	0.83	0.81	1.07

Table 5 - Average correction ratios for quartz and total respirable dust.

	Total	Quartz
CAMPEDS	0.92 ± 9%	0.84 ± 13%
Cyclones	1.60 ± 6%	1.64 ± 9%

Table 6 - Average percentage quartz per sample for different samplers.

	Day 1	Day 2	Day 3
CAMPEDS	46±1	56±1	54±4
Cyclones	38±2	49±3	50±4
Elutriators	42±2	48±4	52±2

peaks in Figure 2 are caused by increases in airborne dust during periods when the crusher is operating. The minimum at approximately 260 minutes corresponds to the lunch break period. Also shown in the Figure is the average of all five minute interval values during the time sampling took place. These daily averages from the Miniram were then compared to the average corrected time-weighted average (TWA) values obtained from all the gravimetric samplers used on that day. Elutriator concentrations were used unchanged while CAMPEDS and cyclone total respirable dust concentrations were corrected using ratios shown in Table 5.

Average Miniram concentrations, and average gravimeteric sampler total dust concentrations are shown in Table 7, along with ratios of samplers to Miniram concentration. Results show that, in spite of the fact that the ratio for DAY 2 is somewhat higher than on either of the two other days, the averages of instantaneous airborne dust concentration values as given by the Miniram are very close to the TWA concentration that would be expected from a BMRC sampler.

SIZE-DISTRIBUTION OF DUST

The size distribution of airborne particulate was found to be very similar for all tests. The average mass median aerodynamic diameter (MMAD) for the three day period was 3.4 μm with a geometric standard deviation (σ_g) of 3.0 which is representative of industrial dust clouds.

DISCUSSION

This section includes discussion of results from the previous section as well as comments on the performance of samplers as used in the field. Discussion will be focused on the performance of cyclones and CAMPEDS (as well as sampling pumps).

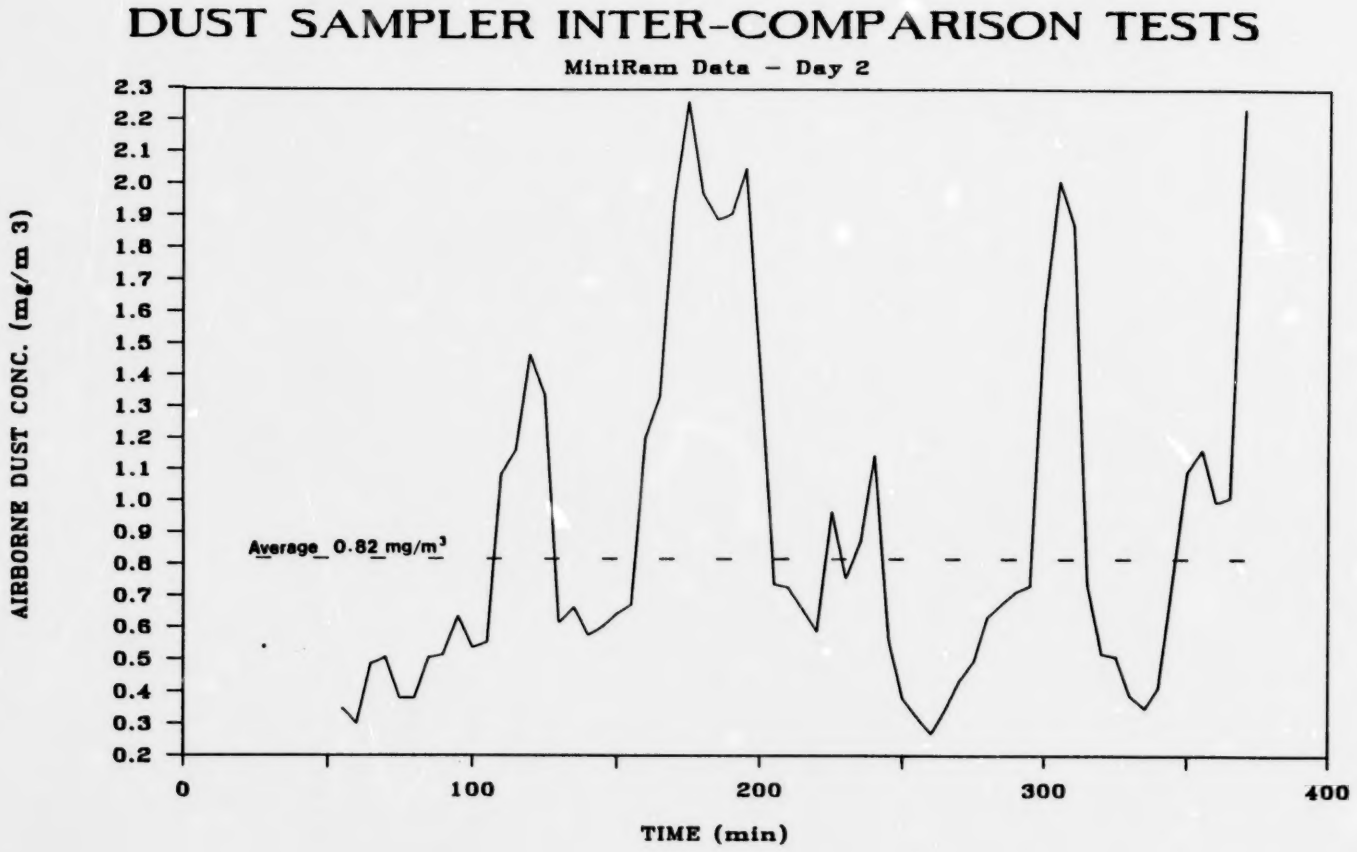

Fig. 2 - Continuous airborne dust concentration profile from Miniram sampler. Also shown, time-weighted average concentration for this profile.

Table 7 - Comparison of time-weighted average total respirable dust from gravimeteric samplers and averaged Miniram dust concentration.

	Day 1	Day 2	Day 3
1-Samplers	0.73	0.90	0.85
2-Miniram	0.85	0.82	1.05
3-Ratio (1/2)	0.86	1.10	0.81
Average ratio:		0.92 $\pm$ 0.12	

10-mm NYLON CYCLONE

The ratio of respirable mass fraction from the elutriator to that of nylon cyclones was 1.60± 6% for total and 1.64 ± 9% for quartz dust. Good reproducibility is apparent from the small standard deviation. The total and quartz dust factor are almost identical. A factor of 1.60, however, is larger than can be explained by the difference in ACGIH and BMRC respirable dust definition. For size-distribution characteristics encountered in this study, the theoretical ratio of dust mass collected should be approximately 1.20 (3,4).

One factor that might cause the cyclone to underestimate the airborne respirable dust mass is the accumulation of electrostatic charges on the non-conducting nylon surface of the cyclone body or on the plastic filter holder. Some research shows that the use of graphite-filled nylon cyclones (5) or simply replacing the plastic filter holder by a metal one (6) may substantially increase penetration of dust to the filter and thereby cause the ratio of 1.60 to be reduced proportionally. This value of 1.60, however, is consistent with laboratory and field work reported elsewhere (7).

On the technical side, the nylon cyclone and the plastic filter holder were easy to manipulate. In Ontario, where these tests were performed, the filter holder consists of three press-fit sections, the middle one being a 1.27 cm cylindrical extension to ensure a more even distribution of dust on the filter surface. The 25 mm filter disc is placed on a relatively thick cellulose support pad. The assembled filter holder is then sealed with a shrinking cellulose ring. This ring is meant to prevent coarse dust accumulating on the outside of the holder from contaminating the filter when it is removed. In high humidity environments this ring became loose as it absorbed moisture from the air.

When loading the filter holder with the support pad and the filter, the

thickness of the pad made it difficult to properly press-fit the assembly together. Approximately one in ten of the holders tested could not be properly assembled when a new support pad was inserted. Because of this, all the filter holders tested in the field were sealed with PVC tape in addition to the cellulose ring. With filter holders sealed in this manner, cases of leakage were not observed during the test.

In spite of the simplicity of the cyclone sampling train, it is felt that the filter holder presently in use has a prohibitively high potential for mechanical failure and introduces a human error factor than cannot be overlooked. A screw-fit filter holder made of conductive material would be a marked improvement to the sampling train. Such a filter holder would be reusable, the potential for human error and failure would be greatly reduced and electrostatic problems associated with this part of the sampler would be reduced if not eliminated.

CAMPEDS

The respirable mass fraction collected by the elutriator to that collected by CAMPEDS was 0.92 and 0.84 for total and quartz respirable dust, respectively. Reproducibility among CAMPEDS samplers was found to be quite good, although not as high as for cyclone sampling trains. This observation is in disagreement with data reported elsewhere (7). The value of 0.92 agrees with laboratory tests performed in a dust chamber using quartz dust (8). The ratio of 0.84 for quartz is very low and as this was not observed in laboratory tests, no explanation can be offered at this point.

Technically, the CAMPEDS is a compact sampler (the whole sampler is the approximate size of the filter holder used with the cyclone). Loading the sampler requires a bit more time than for the cyclone, since the two impaction surfaces require cleaning and recoating between runs. The design, however, greatly reduces the chances of filter contamination by coarse dust and the

sampler seems to be less prone to leakage than the cyclone filter holder. A major drawback of the sampler is the design of the metal filter support grid. This grid has a diameter of 25 mm with 2 mm square openings. A paper washer is placed between the filter and the grid to avoid having filter material stick to the metal grid. This washer introduces a gap between the filter and the grid, close to the edge of the filter. The centre of the filter, however, is in contact with the grid and, as a result, almost all of the samples collected showed a dust deposition pattern with a negative of the grid. Although this does not affect the total respirable dust mass collected, it probably introduces problems or inconsistencies in the assessment of the quartz fraction. A new version of CAMPEDS is now being tested that addresses some of the problems mentioned here.

MINIRAM PDM-3 CONTINUOUS DUST MONITOR

The Miniram was found to be a very useful engineering tool. It allows an instantaneous determination of airborne dust concentration changes brought about by events such as crushing, blasting or sudden changes in ventilation conditions. The sensor was rugged enough to perform well in a variety of situations. Comparison of TWA Miniram data with gravimetric sampler data shows fairly close agreement (see Table 7).

The major drawback of the instrument as a research tool is the format of the data provided by the unit. Data are either supplied at the end of the shift in the form of a time-weighted average measurement or are given as a function of time at the rate of one reading every ten seconds. Data are recorded on a dot matrix printer. It would be desirable to have this amount of data stored in a separate memory unit. The advantages would be twofold: first it would do away with having to carry the printer underground and it would allow the data to be dumped to a micro-computer for processing. The printer was found to be very sensitive to vibration and large amounts of data

were lost in other studies when the unit was exposed to mechanical vibration.

SAMPLING PUMPS

Both sampling pumps were tested on all types of samplers. They operated very reliably throughout the test. The Gilian pump flow rate was adjusted at the beginning of the shift and visual inspection of the rotameter during sampling showed very little decrease in the rate of flow. The Dupont pump has no rotameter and for this reason the flow rate was checked at the end of the shift to verify that the flow rate had not changed. In every case the flow rate had held constant, never dropping by more than 4%.

The Dupont pump's case is more rugged and tamper proof than that of the Gilian. Also, the intake filter protecting the pump mechanism seems to be able to collect a lot more dust before the pressure drop across it begins to pose a problem. In other experiments Gilian pump failure was caused by rapid clogging of the intake filter when sampling in areas where small diesel exhaust particulate was present.

CONCLUSION

This study has shown that the personal gravimetric samplers tested could benefit from simple improvements. It should be noted that the results presented here are obtained from a relatively small set of data. For this reason results should be interpreted carefully and conclusions drawn accordingly. In conclusion it was observed that:

- The cyclone samplers have shown good reproducibility when used side by side underground.
- The difference between cyclones and the BMRC elutriators' respirable mass fraction was more than could be explained by the difference between the BMRC and ACGIH respirable dust criteria.
- The cyclone filter holder design and material has been shown to be a source

of problems and suggestions for improvement are given.

- CAMPEDS samplers have also shown good reproducibility when used in underground environments. Total respirable dust measurement comparisons between the horizontal elutriator and CAMPEDS have shown good agreement.
- Respirable quartz measurements seemed to be overestimated by CAMPEDS samplers.
- The filter support metal grid used in the CAMPEDS samplers are a liability, especially to respirable quartz assessment by X-ray diffraction.
- The Miniram continuous dust monitor tested was found to be a good engineering tool but the data format could be improved.
- Both the Gilian and the Dupont pumps used performed well under field testing conditions. The consistency in rate of flow was reflected in the good reproducibility of gravimetric sampler data.

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